GEOMORPHOLOGY OF THE BARMAH-MILLEWA FOREST

IAN D. RUTHERFURD & CHRISTINE E. KENYON

School of Anthropology, Geography and Environmental Studies, University of Melbourne
Vic 3010, Australia. idruth@unimelb.edu.au

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The Barmah-Millewa forest has excited the curiosity of two generations of earth scientists. This triangle of forest has developed on a low-angle alluvial fan formed by an anabranching network of channels. The Barmah-Millewa forest exists because of the limited hydraulic capacity of the present channel of the Murray River. The result is that flood flows leave the Murray and spread through the forest via a complex network of effluents. The extent and position of those effluents is, in turn, controlled by the fan of palaeo-levees associated with late Quaternary channels of larger size, and coarser sediment load. The morphology of the Barmah-Millewa fan is thus indirectly a product of the rise of the Cadell Fault block, but directly the result of a sequence of channel avulsions. The most enigmatic of six distinct avulsions is the most recent which has taken the river to the south. In a few thousand years the river will make its next avulsion, this time returning to its more natural, northerly, path along the Edward River, to the north of the Cadell Fault block. In this light, the present path of the Murray, via Echuca, could be described as a short-term southern excursion for Australia's iconic river.

Key words: Murray River, Barmah-Millewa Forest, palaeo-channels, climate change, tectonics, stream avulsion

"*[THE NATIVES] endeavoured to explain to us that large water twisted to the N.W. of us, but it did not require their assurances to strengthen my belief that we were gradually entering, deep, into a flooded region, of greater extent, than any I had encountered, for there were sufficient indications of that fact around us; not only did the River deepen in its bed, but, its waters became dark in colour and earthy in taste.*" Sturt (1838, in Sturt 1899).

So said Sturt in 1838, on entering the upstream end of the Barmah-Millewa Forest on his journey down the Murray River. From the air, the Barmah-Millewa Region is a distinctive triangle of forest, with sides of approximately 60 kilometres, comprising nearly 1,800 km^2 (see map at front of Proceedings). The western side of the triangle is defined by a north-south oriented fault scarp of 5 to 15 m height, that stretches roughly from Echuca in the south to Deniliquin in the north. The Murray River enters the triangle at the eastern apex, and exits the area at the south-western point. As described elsewhere in this journal, this triangle of land is distinctive as the world's largest river red gum forest. The forest exists because (a) the capacity of the Murray River decreases through the forest, leading to regular winter-spring flooding (Dexter 1978); and (b) the floodplain of the Murray is not confined, allowing floods to spread laterally for tens of kilometres, and persist for weeks and months. The special hydrological character of the forest is a direct result of the remarkable geomorphic history of this area. The three key elements of this history are climate change, tectonics, and stream avulsion processes.

This paper describes the geomorphology of the Barmah-Millewa region, in order to provide some context for the other papers in this special issue of the Proceedings of the Royal Society of Victoria. We are fortunate that this area has been the focus of several geomorphic investigations, beginning with the astute observations of Harris, a school teacher in Echuca in the 1930s, who was the first to identify the Cadell Fault block (Harris 1939). Later researchers, in the 1960s and 70s, found that the fault block had diverted rivers of different ages, and that these were apparently formed under very different climates, thus providing important evidence of late Quaternary effects on fluvial activity. Interpretations of this record by Bowler and Harford (1966) and Bowler (1978) also stand as classic reconstructions of late Quaternary environments from geomorphic evidence. Interpretation of this remarkable record continues today. The large 1956 and 1974 floods on the Murray River, combined with the increasing importance of the Murray as a conduit for irrigation water, led to some prescient geomorphic investigations by the Rural Water Commission and, later, by the Murray-Darling Basin Commission. Don Currey, in particular, recognized the influence of the small channel capacity, in the Barmah Forest reach of the Murray, on flooding and on irrigation capacities. His 1978 paper with David Dole in the Royal Society of Victoria Proceedings, is also a classic synthesis of the implications of geomorphic history for present river management. Despite this legacy of good work, there are still several tantalizing mysteries about the geomorphic history of this region that we mention, but do not solve.

This paper summarises these earlier studies, concentrating on the morphology of the forest and its streams, rather than on the more contentious interpretation of climatic genesis. The goal is to account for the hydrology and sediments of the forest area. However, we do draw on some remotely-sensed, digital-elevation data that is now available. The Murray-Darling Basin Commission has commissioned laser-borne (LIDAR) surveys of the Murray floodplain, that provide elevation data to a resolution of better than 100 mm. The beauty of these surveys for the geomorphologist and hydrologist, is that the so-called 'last-return' of the laser allows us to see the surface below the tree canopy. Because slopes in the region are so low, geomorphic interpretation by past authors has relied on early irrigation surveys that have not really been improved upon since Harris first used them in his 1939 publication. Thus, this paper provides more detailed physiographic information than earlier efforts.

PHYSIOGRAPHY OF THE BARMAH-MILLEWA FOREST

The region consists of a low-angle alluvial fan with streams of different character spreading out from the apex of the fan at Tocumwal, towards the Cadell Fault block that forms its western edge (Fig. 1). The Barmah-Millewa Forest has a consistent slope from east to west of 0.00025, which represents a fall of 20 m over the 80 km (or 1 m of fall for every 4 km) between Tocumwal and the Cadell Fault. If one follows a NS axis parallel with the ridge of the Cadell Fault, the forest has a slight slope to the north, falling five metres in nearly 80 kilometres (Fig. 2). The northern edge of the fan is clearly delineated from the land to the north that is some 2 to 3 metres higher. The following are the major physiographic features of the region:

1. The Cadell Fault block takes the form of a conic section, with its E-W long-axis being 32 kilometres long, and its N-S section (the Cadell Ridge) being some 60 km long, and forming a curved ridge crest that is a maximum of 15 m high at the centre,

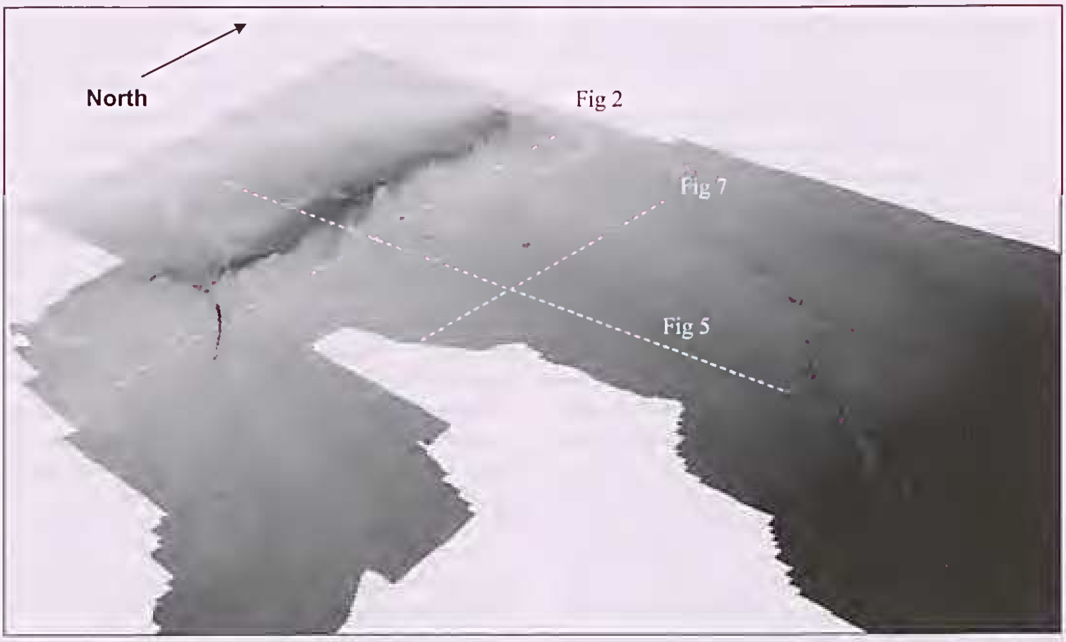

Fig. 1. Oblique LIDAR image of the Barmah-Millewa Forest region (vertical exaggeration x 300). Lines show the paths of cross-sections shown in later figures.

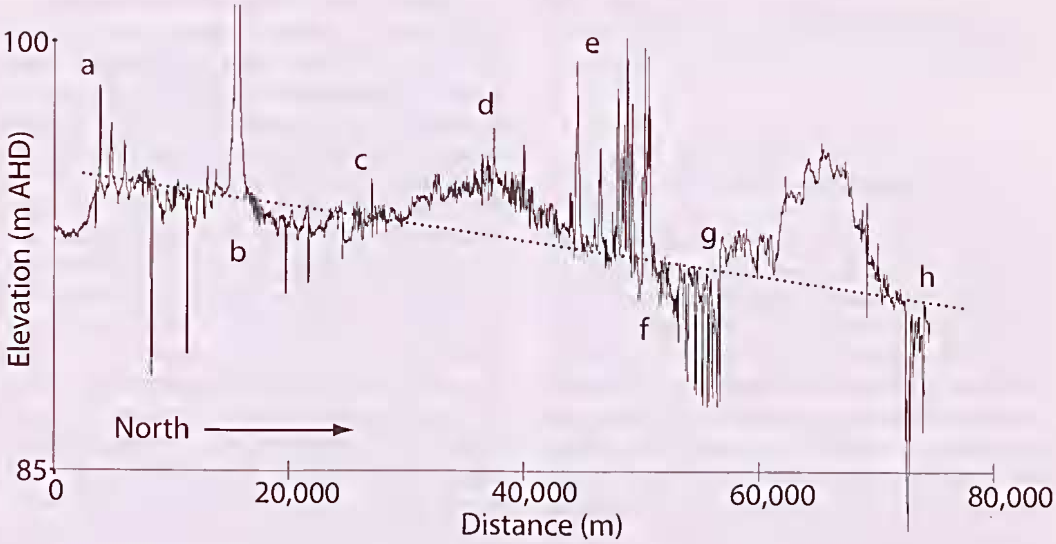

Fig. 2. North-south profile parallel with (but east of) the Cadell Fault. The section runs from Lake Kanyapella northward, across the floor of Lakes Moira and Barmah, and to the Edward River (Location of section shown on Fig. 1). Description of points: (a) Little Lake Kanyapella, with lunette and silt jetties to the north (b) Lunette of Big Lake Kanyapella (25m high – note that this is truncated in the figure) (c) Bed of Moira Lake (d) Bed of Lake Barmah (e) Lunette of the Old Barmah Lake (f) Source bordering dunes from the Ancestral Murray along Gulpa Creek (g) Ancestral course of Gulpa Creek (h) Trench of the Edward River. (Note the extreme vertical exaggeration). (Cross-section based on LIDAR 10 m grid elevation, accurate to 15 cm vertical).

and falling to the north and south. The fault block falls 15 m in 32 kilometres from E to W, producing a slope of 0.00046 which is twice the slope of the Barmah-Millewa forest.

2. There are several palaeo-lake floors in the region. The largest of these is the palaeo-Lake Kanyapella which lies at the southern end of the Cadell Fault. The lake is 20 km NS, and 20 km EW, and extends as far to the west as Echuca. In the south of Kanyapella is a smaller lake (Little Kanyapella) with a diameter of 6 km. The other major lake complex lies immediately to the east of the Cadell Ridge. A large palaeo-Lake Barmah (here called Old Lake Barmah) stretched about 20 km north from the NE edge of Lake Kanyapella (see Kenyon this issue). Nestled within that larger palaeo-lake floor are numerous smaller, active lakes, the largest of which are the Barmah and Moira Lakes, which are presently divided by a silt-jetty of the Murray River. A string of small lake floors lie immediately to the east of the Cadell Ridge.

3. The major source of relief in the region, apart from the Cadell Ridge, is provided by aeolian dune deposits. The highest of these is the large lunette formed at the eastern and north-eastern edge of Lake Kanyapella, known as the Bama Sandhill. This lunette attains its highest point of 25 m immediately where it intersects the Cadell Ridge. The lunette falls in height to the south, being just 8 m high where it is cut by the Murray River, and just three metres high where it is cut by the Goulburn River. Smaller lunettes are formed on the eastern edge of Little Kanyapella (4 m high), and Barmah Lake (from 0.5 to 5 m high) (this is known locally as Bucks Sandhill, and the lunette is followed by the Sandridge Track). The other major aeolian feature is the source bordering dunes. These formed along northern stream banks from sand blown from the seasonally-dry bed of ancient streams by south-westerly winds. Many are now expressed as low mounds up to 1.5 km across and several kilometres long (Lawrence 1988). These are found discontinuously along the northern and eastern side of certain active and inactive streams, and are best preserved along Arutulla Creek, where they are between 4 and 8 m high, and can be up to 1.5 km wide.

4. Fluvial features provide the last distinct geomorphic element of the region. Remnant river channels of different character spread out from the fan apex. The most prominent fluvial features are the 1 m levees of the present stream, and the 2 m

levee of the stream presently occupied by Bullatale Creek. Between the levees, the floodplain floor is criss-crossed by myriad anastomosing channels.

GEOMORPHIC GENESIS OF THE BARMAH-MILLEWA

The Barmah-Millewa forest can be interpreted as one of three low-angle alluvial fans formed by successive avulsions of the Murray and Goulburn Rivers, across the Riverine Plains (Butler 1950). These fans form the great floodplains of the central Murray River. Rutherfurd (1994) describes the Barmah-Millewa fan to the east of the Cadell Fault block, the Gunbower Fan to the south-west of the fault block, and the Wakool fan formed to the north-west. The Barmah-Millewa fan is composed of fine sediments ranging from coarse sand to clay in size, deposited in a complex mix of lacustrine, fluvial and aeolian environments. We will now describe the sequential history of the development of the Barmah Fan.

The general surface of the Riverine Plains (the Shepparton Formation) was deposited by streams that Butler (1950) labelled the 'prior' streams. These distributary streams had low sinuosity, sandy levees, clay swales between the levees, and some source bordering dunes. The prior streams carried sandy bedload, and had well-developed sandy levees that are now characterized by red-brown earths. Channel widths were more than three times larger than present streams. Butler (1958) identified the deposits of the most recent set of prior streams as being a distinct soil formation, characterized by heavy clay sediments that he named the Coonambidgal Formation.

Pels (1964) recognized more complexity in the streams associated with the Coonambidgal sediments, and named these the ancestral streams. These are continuous, sinuous channels with wide, well-defined meander belts (examples can be seen in Fig. 3). The ancestral streams are incised 3 to 5 metres below the level of the general plain; they lack levees, and are tributary (rather than distributary) systems that overlap with many of the modern streams. Today, these channels carry water during floods. Levees and distributaries are absent. Meander wavelengths were more than twice the size of those of the modern river. More recent dating and description has tended to blur the distinction between the prior and ancestral streams. Bowler and Harford (1966) and Bowler (1978) renamed and redated Pels' Coonambidgal sub-units on the basis of evidence from the Goulburn River. More recently, Page et al. (1991) have found older ages for ancestral streams, and have confirmed Bowler's (1986) view that some prior and ancestral streams were coincident. Page

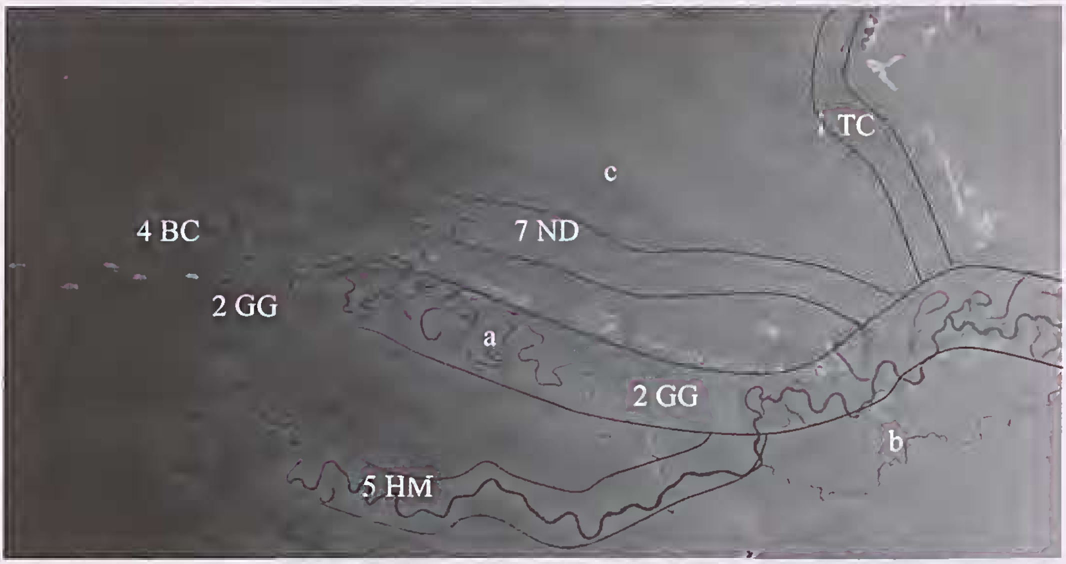

Fig. 3. Apex of the Barmah-Millewa Fan (10 m LIDAR) (Key: 1TC: Stage 1, Tuppal Creek (note source bordering dunes (SBD)); 2 GG: Stage 2 Green Gully/Tallygaroopna channel (again note SBDs on north bank), present path of Aratullah/Cornalla Ck; 4 BC Stage 4, Bullatale Creek avulsion; 5 HM: Stage 5, Holocene Murray avulsion; 7 ND Stage 7, Native Dog Ck; the future path of the Murray River. Points of interest: (a) meanders of Bullatale Ck underfit within larger meanders of the ancestral Green Gully channel; (b) Developing avulsion on the Murray; (c) Prior stream channel remnant.

and Nanson (1996) replaced these terms with 'aggrading' and 'migrational' streams, however these characteristics are not diagnostic.

We will now describe the sequential development of the Barmah-Millewa region, proposing six stages of development over the last 100,000 years or so (Fig. 4). The sequence described here builds on those described by Pels (1966), Bowler (1978, 1986), Currey and Dole (1978), Currey (1983) and Rutherfurd (1990, 1994). The most recent dates have been proposed by Page et al. (1991).

Stage 1: Earliest prior stream/ancestral phase

The Murray River followed multiple paths before the rise of the Cadell Fault (Figs 3 and 4). Rutherfurd (1994) and Currey and Dole (1978) assumed that the earliest path of the Murray in the region was the most northerly. This former channel left the present path of the Murray at Tocumwal and now occupies the northern edge of the Barmah-Millewa fan, cutting into the slightly higher Shepparton Formation. Following the present path of Tuppal Creek, this channel then passed to the north of Deniliquin, joining the present Murray again at the Wakool Junction. It was assumed that this was the oldest channel because it had many classical characteristics of a prior stream: low sinuosity, levees, and well developed source bordering dunes. This channel looks very similar to the low-sinuosity palaeo-channels on the Murrumbidgee River made famous by Schumm (1969). However, using thermoluminescence techniques, Page et. al. (1991) dated this channel at 56,000 yrs BP, which is younger than the Green Gully channels that are usually assumed to be the next path that the river took, which are dated at around 90,000 yrs BP. Thus, there is some doubt about the chronology of these streams.

Stage 2: Green Gully

The Murray avulsed to the south-west from the Stage 1 channel, flowing past the present position of Tocumwal, then due east to join the Goulburn River north of the present position of Echuca (Fig. 3 and 4). At present, this palaeo-channel is called Aratullah Creek. Where this channel is preserved on the back of the Cadell Fault block, the old channel is known as Green Gully. Bowler (1978) suggested that the Goulburn channel that joins with Green Gully was an extension of the large, meandering, Tallygaroopna complex of the Goulburn, that he dated to over 30,000 yrs BP using radiocarbon.

Stage 3: Diversion by the Cadell Fault

Harris (1939) described the truncation of the Murray and Goulburn channels by the rise of the NS Cadell Fault along an extension of the Heathcote-Colbinabbin Axis. The palaeo-channels of the Murray and Goulburn Rivers remain well preserved on the back of the fault block near Mathoura. Many references refer to "the downthrown side of the fault" to the east, yet there is little evidence of the relative movement of the fault. Accurate elevation data from LIDAR allow us to confirm the relative movement of the east and west sides of the fault (Fig. 5). The slopes of the floodplain suggest (a) a lower gradient section, 5-8 km wide, immediately to the east of the fault, and (b) a slight *steepening* of the floodplain from eight kilometers east to about 25 km to the east of the fault. The steepening suggests some slight downthrow of the east side of the fault. Projecting the slopes in Fig. 5 indicates between two and three metres of downthrow over this 25 kilometre zone. The area of lower slope immediately next to the fault is very likely caused by deposition in the lakes that have formed adjacent to the fault, suggesting perhaps two metres of deposition at the particular transect shown in Fig. 5.

Currey (1983) suggests that immediately after the rise of the fault block, the area of the Barmah-Millewa Forest became a large swamp that extended upstream to Tocumwal. There is little evidence for this proposition. Instead the Murray appears to have diverted northward along the face of the fault (the present path of Warrick and Gulpa Creeks, and eventually the present Edward River), to pass around the northern end of the fault block near the present location of Deniliquin. The river diverted to the north because that is the general fall of the land (Fig. 2). Old Lake Barmah did form to the east of the fault block, with dimensions of 20 km north-south and 6 km east-west.

The date when the Cadell Fault first began its activity has been inferred from the age of the stream channels that have obviously been truncated by the fault. Pels (1966), on the basis of his Coonambidgal carbon date of 28,600 BP, suggested that the fault must have started its activity about 30,000 years ago. Similarly, from the age of the Tallygaroopna Channel on the Goulburn River, Bowler (1978) sug-

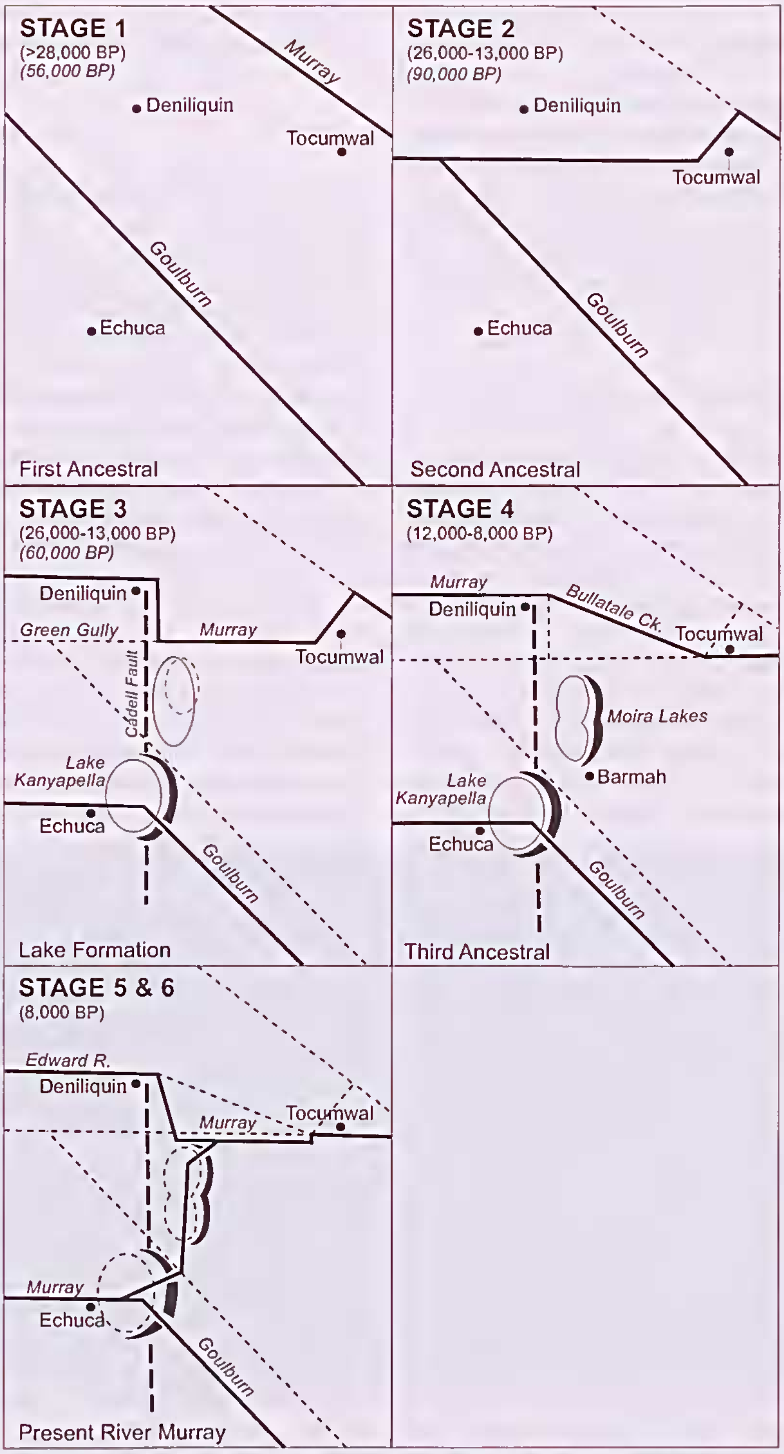

Fig. 4. Schematic diagram showing the six stages of the geomorphic development of the Barmah-Millewa region (note: the figures in brackets refer to the estimated ages of each stage. The upper number in the range refers to the radio carbon dates from Bowler (1978). The numbers in italics refer to thermo-luminescence dates from Page et al. (1991)).

gested a minimum age for the fault of about 25,000 BP. This is further supported by the similar age of Lake Kanyapella, which formed in the fault-angle depression and has been dated at around 30,000 yrs BP by several TL dates (Page et al. 1991).

More recently some doubt has been cast on this date for the fault movement. The TL dates of Page et al (1991) support the 30 to 35 ka BP date for the Tallygaroopna complex, but suggest much older dates for the Green Gully channels of between 65,000 and 94,000 yrs BP. On the basis of this, and other TL dates, Page et al. suggest that the Cadell Fault must have been active much earlier than previously suggested. Thus, all we can say for certain at present is that the fault is older than about 25,000 yrs BP.

Harris (1939) suggested that the fault developed progressively, or episodically, rather than in one step. Fifteen metres of displacement from a single earthquake is highly improbable (Bonilla et. al. 1984) (Fig. 6) and it is much more likely that the fault moved in several small increments. Bowler's (1978) description of the paired terraces in Green Gully supports this view. Further evidence for the gradual rise of the fault is the incision of the Edward River into a five metre deep trench adjacent to the northern edge of the fault block. Thus, we can imagine the Green Gully gradually incising as the fault rose, with the stream ponding to the east of the fault. Eventually the ponded water would have escaped to the north.

To the south of the fault, the freshwater Lake Kanyapella formed. It is not entirely clear why it formed where it did, although Bowler (1978) describes it forming in the "fault angle depression". Page et al. (1991) suggest that Lake Kanyapella did not fill until about 30 ka after the uplift. One to 1.5 m of sediment was deposited on the lake floor, and these sediments are clearly seen in the banks of the modern Murray River. Strong winds transported coarse sands from the NW shoreline to construct a large transverse dune ridge, the Bama Sandhill (Bowler 1986). The lake overflowed to the west into the downstream continuation of the Goulburn River. This channel eventually deepened the overflow and drained the lake. A channel with large meanders (Bowler's Kotupna phase) then incised into the dry lake floor probably before 15,000 BP.

Stage 4: Bullatale Creek avulsion

Some time between 25,000 yrs BP and about 10,000 yrs BP, the Murray River avulsed from the Tullah Creek palaeo-channel (about 40 km upstream of

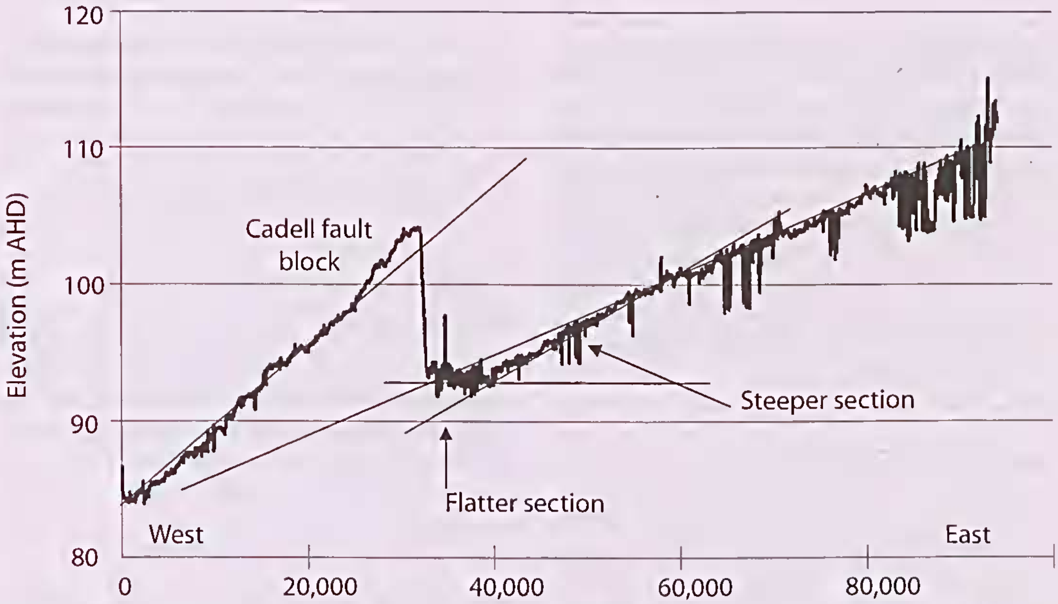

Fig. 5. 100 km west-east transect from the back edge of the Cadell Fault block to the west, to the upstream edge of the Barmah Forest at Tocumwal. Note the extreme vertical exaggeration of this section. Location of the section is shown on Fig. 1

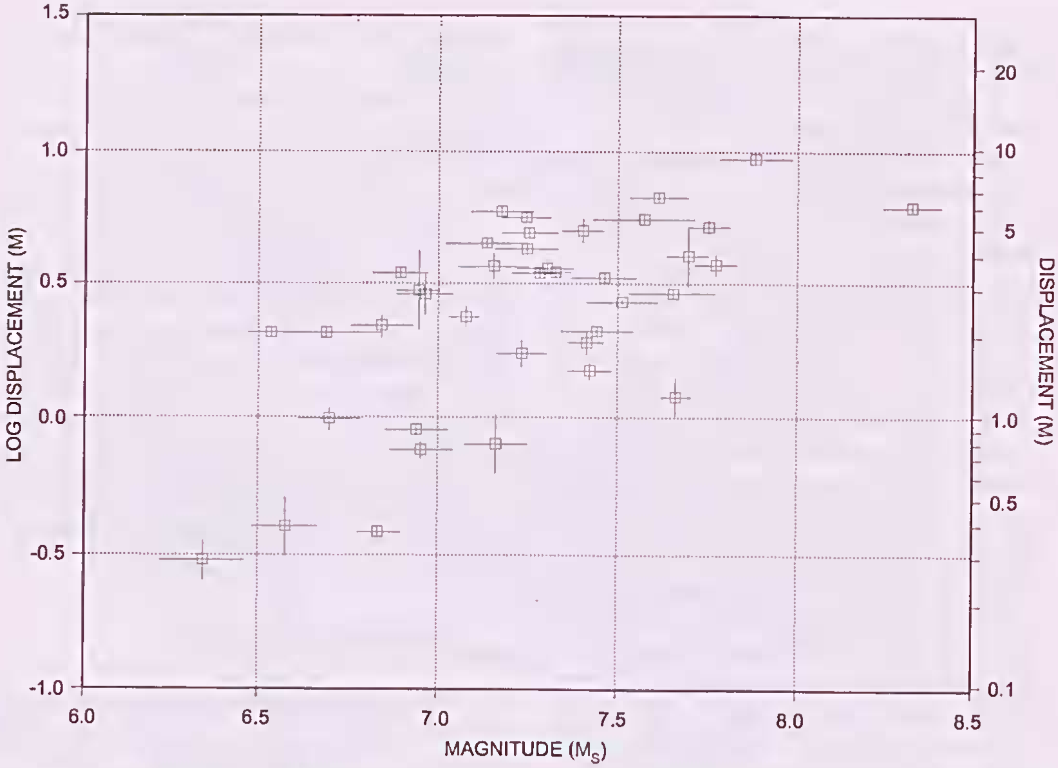

Fig. 6. Vertical displacement (rupture) associated with earthquakes of different magnitude (adapted from Bonilla et al. 1984)

Gulpa Creek), into a sinuous channel that is now occupied by Bullatale Creek. During the same period, Lake Kanyapella was seasonally filled by the Goulburn River, with seasonal winds forming the prominent lunette on its eastern shore. Old Barmah Lake was also full in this period, perhaps fed by overflow from the Gulpa Creek path of the Murray. Lunettes of up to 5 m formed. Barberis (1983) suggests that the lake would have had to be up to 2 m deep to form these lunettes. She also describes the deposits in the lake as consisting of silts and fine to medium sands, and surprisingly little clay.

Stage 5: The Holocene Murray

The next avulsion of the Murray left the Bullatale Creek course about 8 km downstream of the modern position of Tocumwal, and flowed south west. Both Pels (1966) and Bowler (1978) suggest that this avulsion formed the modern Murray that led to the south. Currey (1983), on the other hand, suggests the more probable path, that was for the Murray to come up against the levees of Gulpa Creek, and so divert north into the present path of the Edward River. There are no direct dates for this avulsion, but it is likely to have occurred around the start of the Holocene, based on a carbon date of the Goulburn River. The channel that avulsed at this time was very unlike earlier phases of the river. The river was narrow, with high proportions of silt and clay, and poorly developed point bars.

Around this time, both Lake Kanyapella and Old Barmah Lake were probably drying out, to be replaced by smaller, inset lakes: Little Kanyapella and the smaller Barmah Lake. These smaller lakes developed small lunettes of their own.

Stage 6: the Holocene/Modern Murray

The final, and most enigmatic, avulsion of the Murray was to the south from Picnic Point at the Edward River offtake (Figs 3 and 4). The river cut through the lunette of Old Lake Barmah, across the flat floors of Lake Barmah and Lake Moira, through the 8 to 10 m high southern end of the Kanyapella lunette, to join the Goulburn River on the floor of Lake Kanyapella. From a single radiocarbon date, Bowler (1978) dated this southerly channel to about 9,000 yrs BP. However, this date is more likely to provide a date for the Murray-Edward channel rather than the most recent path of the river. All we can say is that the most recent avulsion is less than about 9,000 years old.

As discussed below, this most recent path of the Murray is unusually straight, with poorly developed point bars. This Murray channel has deposited a digitate delta (or silt-jetty) across the floor of Young Barmah Lake, cutting the lake in half, with Moira Lake being to the west and Barmah Lake to the east.

To summarise, studies of the Barmah-Millewa region have led investigators to propose various avulsions and paths followed by the Murray and Goulburn Rivers. In reviewing that literature, we propose six major changes in the position of the Murray River over perhaps 60,000 years, and certainly over 30,000 years (Fig. 4). Four of these avulsions occurred after the rise of the Cadell Fault block. Each of these channels has had different planform, and channel dimensions, associated with both climate change and with the intrinsic sequence of channel changes associated with the avulsions themselves. Clearly, channel avulsion is the key mechanism driving the geomorphology of the Barmah-Millewa region. We now discuss the avulsion mechanisms in more detail.

AVULSION MECHANISMS IN THE BARMAH-MILLEWA

Some people have described the Barmah-Millewa forest as a swampy area formed behind the fault block. Other authors describe the Cadell Fault "defeating" the Murray River (Harris 1939) or "placing an obstacle across the river's path", or "diverting" the river (Bowler 1978; Currey 1978). None of these descriptions really capture the key mechanisms that are driving the morphology of the Barmah-Millewa area, which is about the geomorphic mechanisms that forced the river to occupy new courses.

The first point is that there is no *a priori* reason why the fault should have "defeated" the river. As discussed above, the fault probably rose in steps of a metre or less, and the Green Gully palaeo-river was clearly able to incise and keep-up with the rate of height increase. The reason for this incision was that the slope of the channel was increasing as the fault block rose, enabling the river to cut into its bed. The eventual defeat of the river was almost certainly linked to the late-Pleistocene decline in the discharge of the Murray and Goulburn rivers, described by Bowler (1978). Despite the increase in bed-slope, the decline in discharge meant that the river was no longer capable of incising its bed.

The general template for the Barmah-Millewa Forest existed before the rise of the Cadell Fault block. The confined floodplain of the Ancestral Murray at Tocumwal already existed before the fault, and a series of channels spread out from that point. Thus, we cannot argue that all of the avulsions relate to the effect of the fault. However, the fault did produce a perfect situation for the development of avulsions in this environment, as we will now discuss.

Recent research into the mechanisms of channel avulsion (Judd et al. 2004) has demonstrated that the two essential features required for an avulsion to occur are (a) water spilling out of one channel onto a floodplain, and (b) a steep hydraulic (i.e. energy) slope where that water re-enters a second channel. The basic hydraulic mechanism that drives the avulsion is the hydraulic slope at the downstream reentry point. Thus, avulsions develop from downstream up, following the path of highest flood flow velocity across the floodplain. Contrary to popular opinion, the stream does not flow over a levee and cut a new channel across the floodplain. Such 'crevassing' usually produces short effluent channels that spread-out rather than incising. The rise of the Cadell Fault produced a perfect situation for avulsions to develop, because it encouraged overbank flows, and because it produced channels at right-angles to the floodplain flow.

The fault encouraged overbank flows by converting confined floodplains into unconfined, vertically accreting channels. Consider the Stage 2, Green Gully system (that follows the present path of Cornulla Creek). As the fault block rose, the Green Gully system incised into the back of the fault block, and the eastern channel began to pond. The ponding produced a hydraulic backwater effect that, in this low slope environment, extended upstream for tens of kilometers. A contemporary example of a similar process is the backwater effect of the Torrumbarry Weir on the Murray. The backwater from this weir affects flow and overbank flooding, for 80 km upstream, to Echuca. The change in confinement caused by the backwater of the Cadell Fault changed the Murray from a laterally accreting meandering system above Tocumwal, to a vertically accreting system below Tocumwal. This is evidenced by the absence of a significant number of billabongs, oxbow lakes and meander swales on the Barmah Fan (Rutherfurd 1994).

The result of the backwater was that the Green Gully ancestral stream began to deposit levees, which is an indication of increased overbank flood frequency. The alluvial ridge from this flooding is now 2 m high along the Cornulla Creek (Fig. 7). The more frequent overbank flows from the Green Gully channel travelled westward to join the Gulpa Creek path of the river, that was flowing northward around the fault block. Where floods strike a channel at right angles, it is a perfect hydraulic situation to develop a steep energy slope into the channel, producing scour that will cut back up from the re-entry point.

Once the cycle of avulsions is started, they are self-perpetuating (Schumm et al. 1996) with the next avulsion occupying the low area between the levees of past channels. This explains the present path of the Edward River, as it runs northward, parallel with the levee of Gulpa Creek.

All of the avulsions of the Murray River since the rise of the Cadell Fault can be readily explained by the avulsion model described above, with the exception of the most recent avulsion. After several millennia of flowing to the north of the fault block, the river, about 9,000 year ago, avulsed to the south, from Picnic Point. This avulsion is a surprise because (a) it developed from the present path of the Edward River, which does not have a well developed levee; (b) It does not appear that the avulsion channel followed a 'hydraulically connected' path. That is, assuming that the avulsion progressed upstream from the Goulburn River, it had to pass upstream through the 8-10 m high lunette of Lake Kanyapella, then cut across the flat floor of Old Barmah Lake, through the 5m lunette of Old Barmah Lake, and thence up to the Murray. (c) The general slope of the land in this area is toward the north, which would argue against major flood flows passing to the south from Picnic Point.

We cannot explain this avulsion at present, but it is worth recording a story described by Dr Wayne Atkinson about the Yorta Yorta people (Atkinson, this issue). The story goes that the Barmah-Millewa Forest was flooded so that only the tops of the sand-dunes were above the flood-waters. The Yorta Yorta people sheltered on the top of the Bama Sandhill (the Kanyapella lunette), and waited for the water to go down so that they could find food again. But the flood stayed up for many weeks. They decided to cut a channel through the lunette and let the water out. This they did with digging sticks. Not only did the water run out, but it cut a new channel that diverted the river to the south. Although there are some hydraulic problems with developing a channel in this way, this story deserves some detailed investigation. It is certainly an interesting explanation for an enigmatic avulsion.

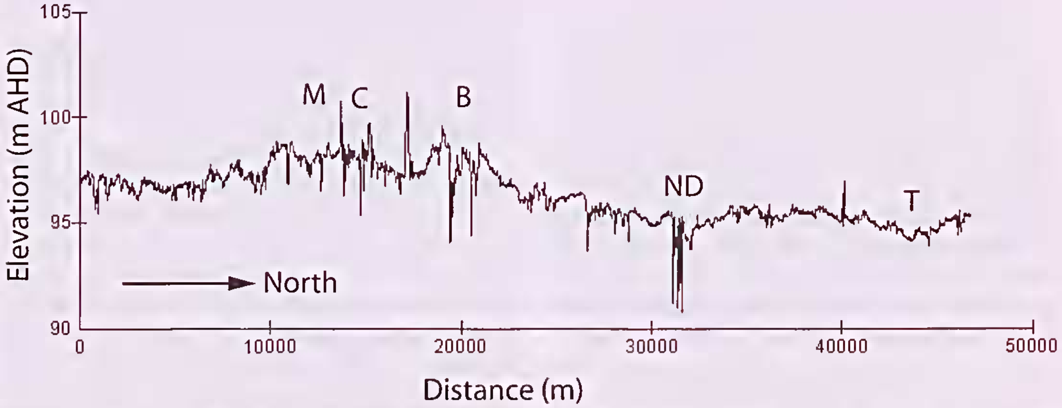

Fig. 7. North-south cross-section through the Barmah-Millewa region (along longitude 145° 10') (location of section shown on Fig. 1). Key: M = present position of the Murray River; C = Cornulla Ck, path of the Green Gully ancestral channel; B = Bullatale Ck, the Stage 4 ancestral path (note the prominent natural levees); ND = Native Dog Ck (future path of the Murray River); T = Tuppal Ck, path of Stage 1 channel.

Finally, it is possible to predict where the next avulsion of the Murray will take place. Given the relative elevations of the floodplain, the next path is almost certain to again return the river to its northern path. The avulsion is already developing along the present course of Native Dog Creek, about 5 km downstream of Tocumwal. The floodplain of this channel is nearly four metres lower than the alluvial ridge formed by former channels (Fig. 7). We do not know how fast the Native Dog Creek is developing, but the head of the creek is less than two kilometres from the Murray River. We would expect the avulsion to develop rapidly once it joins to the Murray, perhaps developing over centuries. If one accepts the pre-Page et al. (1991) dates for the Cadell Fault, then there has been a major avulsion of the Murray every 4,000 to 5,000 years. The character and discharge of the river has altered greatly over that time, so we cannot assume that this frequency should continue.

MODERN MORPHOLOGY AND HYDROLOGY OF THE BARMAH-MILLEWA FOREST

The morphology of the Murray and Goulburn Rivers, and their myriad palaeo-channels and anabranches, control the hydrology of the Barmah-Millewa forest. This was well described by Currey and Dole (1978), by dividing the river into three tracts. We expand on their description here with some data on channel dimensions taken from Gippel and Lucas (2002).

Corowa to Bullatale Ck offtake

There is a dramatic contrast between the Corowa-Tocumwal reach, which has a narrow, confined floodplain 3 km in width; and the unconfined, leveed channels of the Barmah-Millewa Fan. Between Corowa and Tocumwal, the river has bankfull widths of 90 to 210 m, with a median of 130 m, and bankfull depths of 5.5 to 10 m with a median of 7 m. The active floodplain is approximately 7 m below the Riverine Plain. One of the most prominent features in this reach is the sandy beaches on the point bars. The whole discharge of a major Murray flood passes virtually unattentuated along this reach (Currey & Dole 1978).

Bullatale Creek to Picnic Point

This reach is delineated by the change in flood hydrology occurring at the offtakes to Tuppal and Bullatale Creeks at the upstream end, and the Edward River anabranch offtake at the downstream end. The morphology of the Murray River changes dramatically when the river enters the Barmah Forest tract (as defined by Currey & Dole 1978), with the most prominent change being the decrease in sinuosity, and the absence of the large bends with their sandy point bars that are common upstream. Natural levees, comprised of silty-clay, are generally present on both banks, sometimes in excess of 1 m higher than the surrounding floodplain. Bankfull width is 50 to 160 m, with a median of 85 m; bankfull depth is 3.3 to 8 m, median 5 m.

Channel capacity decreases from around 25,000 ML/d at Tocumwal, to around 8,500 ML/d at Picnic Point. Many effluents leave the Murray to feed networks of anabranching channels. Most of the flow passes north into the Edward River system, but some, such as Gulf Creek (Fig. 8), pass water to the SW via a web of anabranching channels that returns to the Murray River downstream of Picnic Point. These flows are hemmed in to the south by the natural levees of Broken Creek, which is an ancestral path of the Goulburn River. The freeboard for summer regulated flow level decreases from 4 m to 0.1 m below top of bank in the Picnic Point area (Fig. 9). The lunettes and natural levees on the Murray in the Barmah reach form a natural choke, or flow constriction, known as the Barmah Choke. Although this whole reach gradually decreases in capacity downstream (Fig. 9), the narrow and constricted reach of channel from just upstream of Picnic Point to Barmah, is specifically labelled as "The Barmah Choke".

Flood flows through the Barmah Choke are greatly attenuated by the large storage capacity of the forest. As flow in the channel approaches bankfull, flow is diverted into effluents (Fig. 8), and so into the Edward-Wakool system, or into the Barmah forest. As shown by Currey and Dole (1978), during the flood of 1975, 55% of the total discharge passing Tocumwal overflowed into the Edward-Wakool system. Even during very large floods, when channel capacity is exceeded, peak flow through the Barmah area of the river does not exceed 30,000-35,000 ML/d, even though flows at Tocumwal may exceed 200,000 ML/d (Currey and Dole 1978) (Fig. 10). On some occasions, flood flows from the

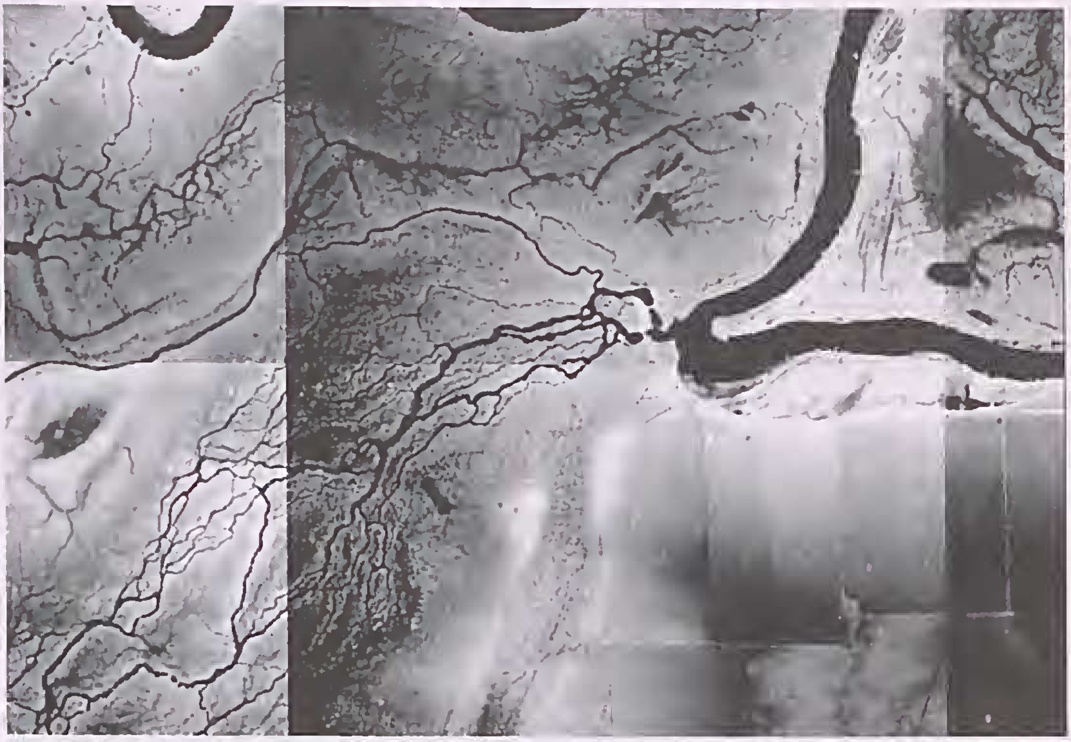

Fig. 8. A maze of anabranching channels (Gulf Creek) fed by an effluent at Yielima Bend, halfway between the Bullatale and Edward effluents. Note the regulator across the mouth of the effluent. This is known as the 'Gulf' Regulator. (1 m LIDAR grid data).

Goulburn and Campaspe Rivers have been sufficient to force Murray waters to back up, and in the vicinity of Barmah to reverse the normal flow direction (Currey and Dole 1978). Broughton (1966) describes how, in the great flood of 1870, the flood in the Loddon River was sufficient to back up the Murray. Logs floated out of the Loddon River, upstream for 100 km, into Thule Creek, and thence into the Edward, finally returning to the Murray at the Murrumbidgee Junction.

Picnic Point to Bama Sandhill

Channel capacity in this reach increases downstream from around 8,500 ML/d at Picnic Point to a major flood capacity of 35,000 ML/d maximum at the lower end. Freeboard increases dramatically from around 1 m to 4 m above summer regulated flow level (Fig. 9). The dimensions of the channel increase because all effluent flows moving through the forest re-enter the Murray in this reach.

The river has low sinuosity, and meanders are irregular and generally low angle and low amplitude. Channel width and depth increase downstream; bankfull width ranges 38 to 210 m, with a median of 65 m, and bankfull depth ranges 4 to 10 m, with a median of 5 m.

Bama Sandhill to Goulburn River Confluence

In this reach the river leaves Currey and Dole's Barmah Forest Tract to join the Ancestral Goulburn Tract. The river through this reach has low sinuosity and is cut through the bed of the former Lake Kanyapella. The meanders have short wavelengths and low amplitude. Nearing the Goulburn River, the Murray River channel adopts a much more sinuous plan form as it crosses onto the sandy sediments of the ancestral Kotupna channel of the Goulburn. Channel size is relatively constant, with bankfull width of 80 to 90 m with a median of 90 m. Bankfull depth is 7 to 9 m. Mud drapes are prevalent on

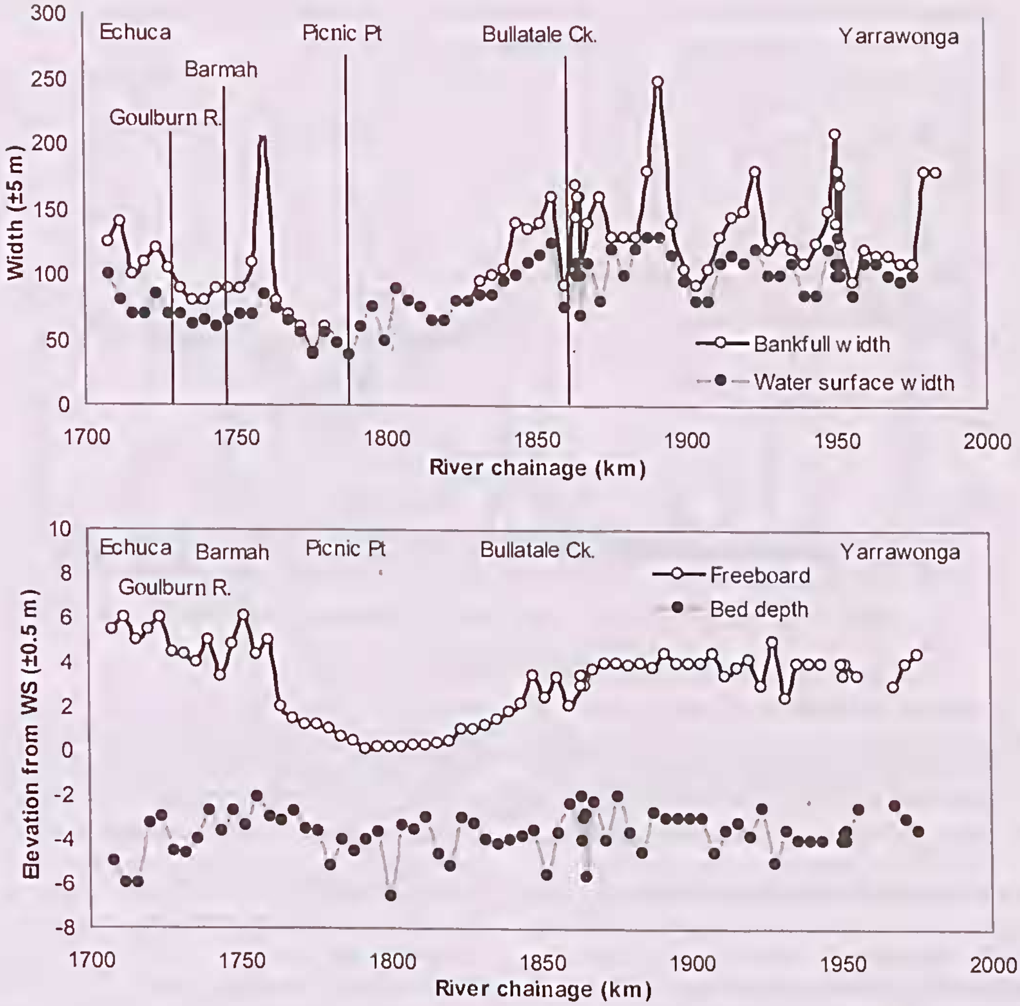

Fig. 9. Dimensions of the Murray River from Yarrawonga to Echuca (From surveys by Gippel and Lucas 2002).

all banks over *in situ* silty-clays. There is a distinct sedimentary boundary approximately 2 m from the top of the bank (the bed of Lake Kanyapella). Small low level sandy point bars reappear in the channel in this reach.

A footnote to this geomorphic history is that Harris (1939) named the Cadell Fault after Francis Cadell, the paddle-boat captain who won the famous race up the Murray River in 1853. The purpose of the race was to encourage development of the Murray as a navigation route. Captain Cadell then spent much of his career removing snags from the Murray and its anabranches to allow boats to navigate these small and tortuous channels. Ironically, it was the action of Cadell's namesake fault that forced the larger paddle-boats to terminate their journeys at Echuca, because the Barmah Choke was too small to allow passage further upstream.

HISTORICAL GEOMORPHIC CHANGES

Holocene geomorphic changes have been modest due to low discharges and a resistant channel boundary. Point bars are confined, and tend to migrate strongly downstream. Complex effluent channels are developing on the floodplain (Fig. 8).

There have been two measurable changes to geomorphic processes since European settlement: increased floodplain sedimentation rates, and increased bank erosion rates. Rates of vertical accretion of the floodplain have been estimated from

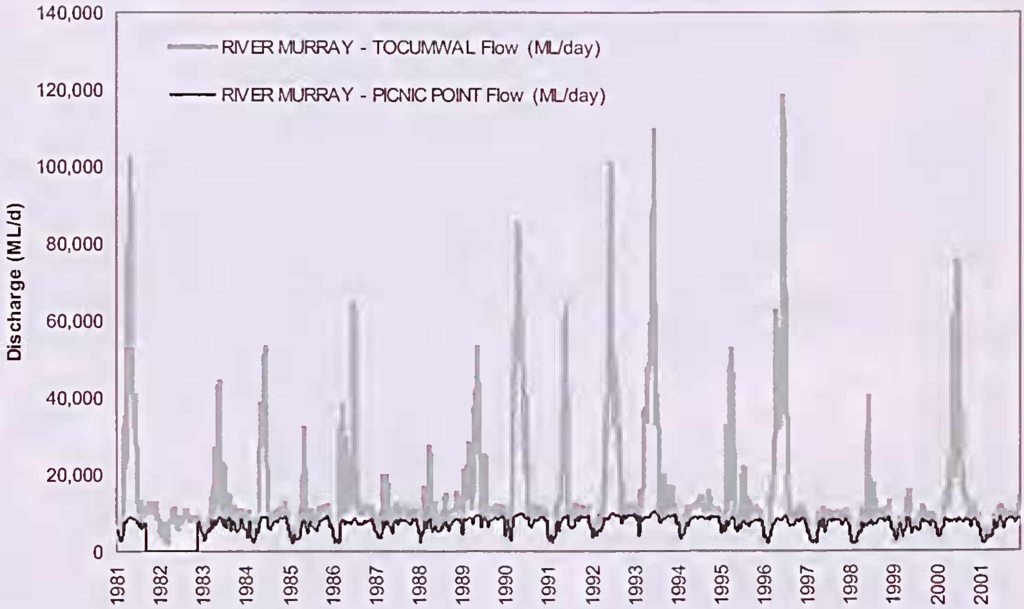

Fig. 10. Daily discharge record for Picnic Point (Barmah Choke) and Tocumwal.

the first appearance of exotic pollen (Kenyon & Rutherfurd 1999; Kenyon 2001). A historical floodplain deposition rate of 7 mm/10 years compared with assumed long-term background rates of 3 mm/10 yrs. While this rate is low, it still suggests a doubling of the floodplain sedimentation rate since European settlement.

The other major historical channel change is widening, as reported by Rutherfurd (1992) and Gippel and Lucas (2002). From Yarrawonga to Bullatale Creek, between 1876 and 1981, the Murray widened at bankfull level by an average of about 30 to 40 m. Through the Barmah Forest (from the Bullatale Creek offtake through to the Goulburn River junction) the river has widened much less, by about 3 to 15 m (Fig. 11). The cause of the widening appears to be related to the maintenance of long duration flows through the irrigation season, worsened by boat wash, and degradation of once extensive *Phragmites* beds. Along much of the river one can see benches cut into the banks at the level of the regulated flow. Rutherfurd (1992) reported the tread of the benches as usually being 2 to 3 m wide, but after the regulated flow level was lowered in April 2002, Gippel and Lucas (2002) observed exposed benches up to 20 m wide.

Since the 1960s there have been attempts to increase the capacity of the Barmah Choke because it represents a serious limit on the amount of irrigation water that can be delivered along the Murray to the irrigation areas west of Echuca (see Ladson & Chong this issue). The main activity has been removing timber from the stream (desnagging). For example, from 1982 to 1984, 605 snags were removed and 4,548 willows were lopped (River Murray Commission 1984). The effect of this work on channel capacity has been debated, but an exhaustive review by Gippel and Lucas (2002) suggests that bankfull flow capacity through the Choke may have increased by 5 to 10 %.

CONCLUSIONS

There is a reason why the Barmah-Millewa forest is a popular destination for geomorphology field trips, and why it has excited the curiosity of two generations of earth scientists. In one triangle of land is encapsulated the complex interactions of climate and tectonics on channel form, and so on hydrology, with the forest being the biological result.

Despite 65 years of study, the complex geomorphology of the Barmah-Millewa region still has some unresolved questions. Here are some of them:

1. The absolute ages of the Cadell Fault and of the various ancestral channels. The consistent

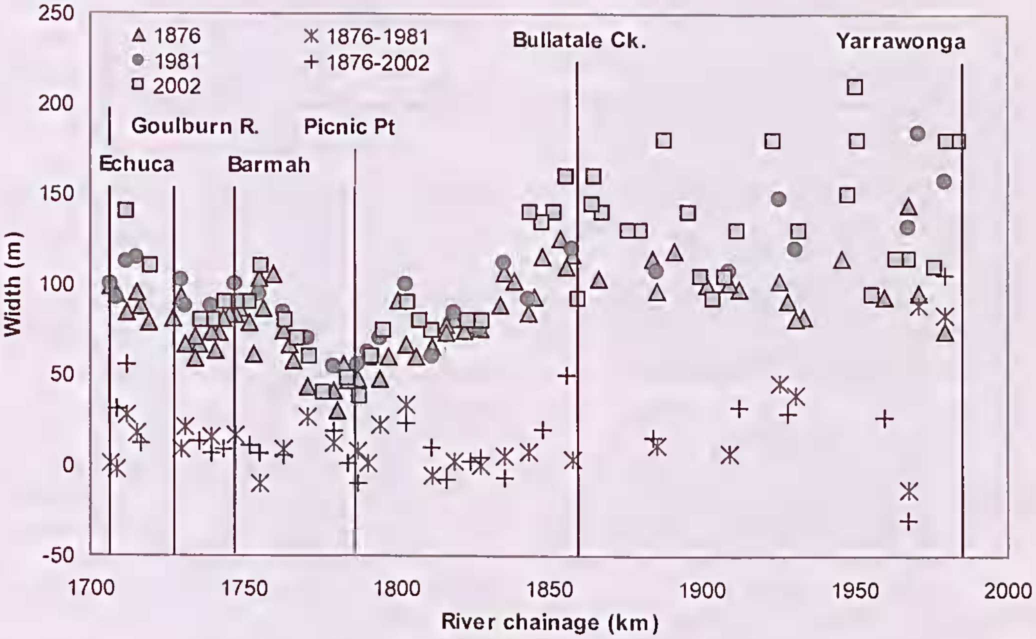

Fig. 11. Historical width change of the River Murray at symmetrical cross-sections, Yarrawonga to Echuca, from three surveys. The 2002 survey was conducted by Dr Chris Gippell and reported in Gippel and Lucas (2002). The crosses show the change (in metres) between the 1876 survey widths and the two later surveys. Cross-sections were considered to coincide if they were within 600 m chainage, but even this liberal interpretation produced only a small number of coincident cross-sections for comparison of the 2002 survey with earlier surveys.

chronology of Bowler (1978) and others has been complicated by the thermoluminescence dates of Page and his colleagues. These dates have tended to confirm that Pels' neat distinction between the prior streams (before the Cadell Fault) and the ancestral streams (after the fault) is not so simple. There is little doubt that some of the channels were contemporaneous.

2. Did the Cadell Fault rise gradually or episodically? Recent measurements are suggesting that the fault may still be active (Dan Clark, Geoscience Australia, personal communication).

3. The actual mechanisms and processes of channel avulsion require more work, particularly the interactions between tectonics and avulsion. Probably the most interesting mystery is what triggered the southward avulsion of the Murray at Picnic Point. As discussed above, this avulsion appears highly improbable. The avulsion had to develop from the downstream end, and the channel would have to have cut through the almost level floor of Lake Kanyapella, through the 8 to 10 m high Bama Sandhill, across the flat floor of Old Barmah Lake, and finally through a 4 to 5 m lunette. And all of this occurred against the regional slope of the land.

The Barmah-Millewa forest exists because of the limited hydraulic capacity of the present channel of the Murray River. The result is that flood flows leave the Murray and spread through the forest via a complex network of effluents. The extent and position of those effluents is, in turn, controlled by the fan of palaeo-levees associated with late Quaternary channels of larger size, and coarser load. The morphology of the Barmah-Millewa fan is thus, indirectly a product of the rise of the Cadell Fault block, but directly the result of a sequence of channel avulsions. In a few thousand years the river will make its next avulsion, this time returning to its more natural, northerly, path along the Edward River, to the north of the Cadell Fault block. In this light, the present path of the Murray, via Echuca, could be described as a short-term southern excursion for Australia's iconic river.

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